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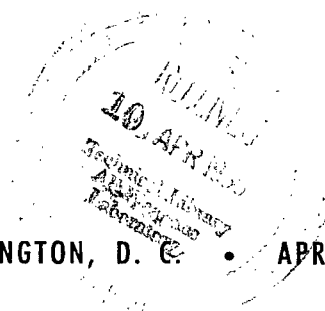
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# AN EXPERIMENTAL INVESTIGATION OF THE EFFECT OF GRAVITY ON A FORCED CIRCULATION PATTERN IN SPHERICAL TANKS

*by Steven G. Berenyi, Ralph C. Nussle, and Kaleel L. Abdalla*

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# AN EXPERIMENTAL INVESTIGATION OF THE EFFECT OF GRAVITY ON A FORCED CIRCULATION PATTERN IN SPHERICAL TANKS

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## SUMMARY

An experimental investigation of the effect of gravity on a forced circulation pattern in spherical tanks was conducted. The tank systems tested were exposed to acceleration levels of approximately 0.005, 0.01, 0.02, 1.0, and less than  $10^{-5}$  g. The flow pattern of an axisymmetric wall jet was experimentally established in three different size tanks. The results indicate that the minimum jet inlet velocity required to establish and maintain the flow pattern is a function of jet inlet thickness, tank radius, and gravity level.

## INTRODUCTION

Capability for advanced space missions relies on the development of multistart vehicles with high energy cryogenic upper stages. Some concepts of these stages are detailed in reference 1. These vehicles will be exposed to solar radiation during zero-gravity coast periods which, in turn, will cause tank internal pressure to rise. To maintain design tank pressures, it will become necessary to vent the tanks in a zero- or low-gravity environment without excessive loss of inert pressurant gas or liquid propellant. One venting method that has been proposed which is independent of whether liquid or vapor is adjacent to the vent valve is to pass the fluid to be vented first through the vent valve and then through a heat exchanger located in the tank. The heat exchanger takes heat from the tank fluid and vaporizes the vented fluid such that it is discharged at a higher enthalpy. For successful operation this system requires that the warm liquid along the tank wall and any entrapped vapor bubbles be circulated from the wall to the heat exchanger. A forced circulation pattern which appears attractive for this venting system is one in which the fluid is washed along the tank wall and returns to the generating device as a liquid core in the center of the tank with or without entrained vapor bubbles (see fig. 1). A detailed analysis of a complete heat removal system may be found in reference 2. In order to help evaluate or possibly to predict the formation of such a flow

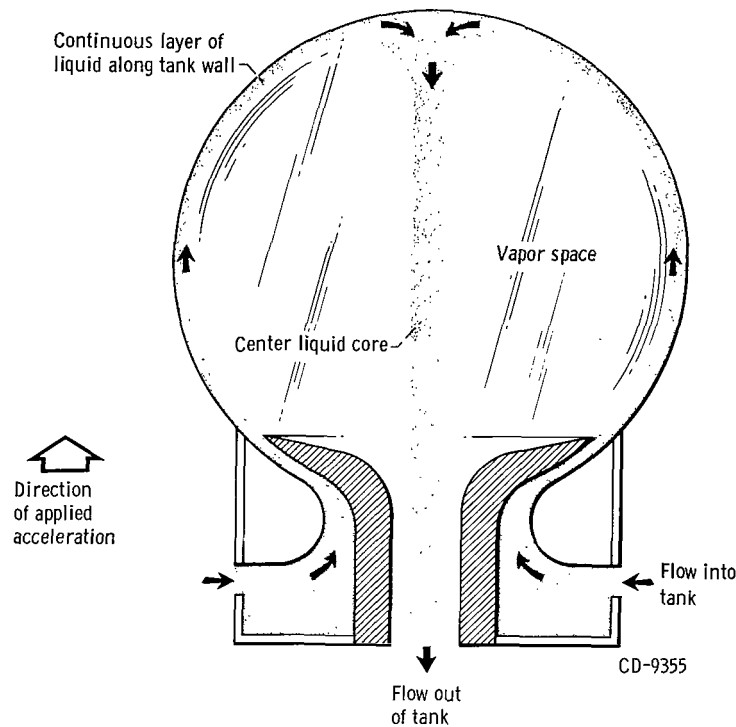


Figure 1. - Desired circulation pattern.

pattern in reduced gravity, criteria governing this flow pattern formation are necessary.

To date no applicable literature on axisymmetric wall jet behavior in reduced gravity environments has been found. Numerous papers are available on the analysis of plane wall jet velocity profiles and maximum velocity decay along a surface at normal gravity (refs. 3 to 7). These jets, however, are not analogous to the problem under investigation and are somewhat beyond the scope of this report. Furthermore, a comprehensive program, including instrumentation for measuring jet velocity profiles, would be required to extend these works to reduced gravity environments. At present, velocity profile measurements of three-dimensional, thin wall jets in ground based reduced gravity facilities (drop towers) is impractical because of the relatively short test times available.

The purpose of this work is to evaluate circulation performance for scaled propellant tanks in normal gravity, low gravity, and in a near zero-gravity environment (weightlessness). The investigation was limited to experimentally establishing and maintaining a flow pattern which results in complete circulation of all the liquid in the tank and in determining the effects of low-gravity environments on this pattern. A secondary objective of the experiment is to formulate a scaling law with which to predict the formation of this flow pattern in zero gravity from normal gravity tests.

The experiments used geometrically similar spherical tanks. The 2.3-second

drop tower facility at the Lewis Research Center was used for the tests. The tests were conducted at gravity levels of approximately 1.0,  $10^{-2}$ ,  $10^{-3}$ , and  $<10^{-5}$  times earth gravity. The reduced or partial gravity was obtained by a unique system which provided acceleration to the freely falling drop package. The circulation pattern was set up by externally pumping liquid to the tank through an annular inlet nozzle. Average jet inlet velocities were calculated, and the flow patterns were documented in high-speed motion pictures.

## SYMBOLS

D	tank diameter, cm
d	jet inlet annulus diameter, cm
g	acceleration due to gravity, $980 \text{ cm/sec}^2$
n	a coefficient
R	tank radius, cm
V	jet inlet velocity, cm/sec
x	tank outlet diameter, cm
$\delta$	jet inlet thickness, cm

## APPARATUS AND PROCEDURE

### Test Facility

These tests were conducted in the Lewis Research Center's drop tower shown in figure 2. In this facility the experiment was allowed to free fall inside a protective air drag shield thus minimizing the air drag on the experiment. In this manner the effects of air drag on the experiment were kept below  $10^{-5} g$ . A free-fall distance of 26 meters allowed a 2.3-second period of weightless test time. A sandbox was used at the bottom of the drop tower to decelerate the falling experiment. Three maple spikes with aluminum tips were attached to the bottom of the drag shield and were used to decelerate the system upon impact with the sand. A more detailed description of the test facility may be found in reference 8.

In this series of tests, gravity levels in the range of 0.005 to 0.02 g were obtained by the use of a thruster system on the drop package. For the free-fall drops ( $<10^{-5} g$ ), the thruster was not used and the package was allowed to fall from the top of the drag

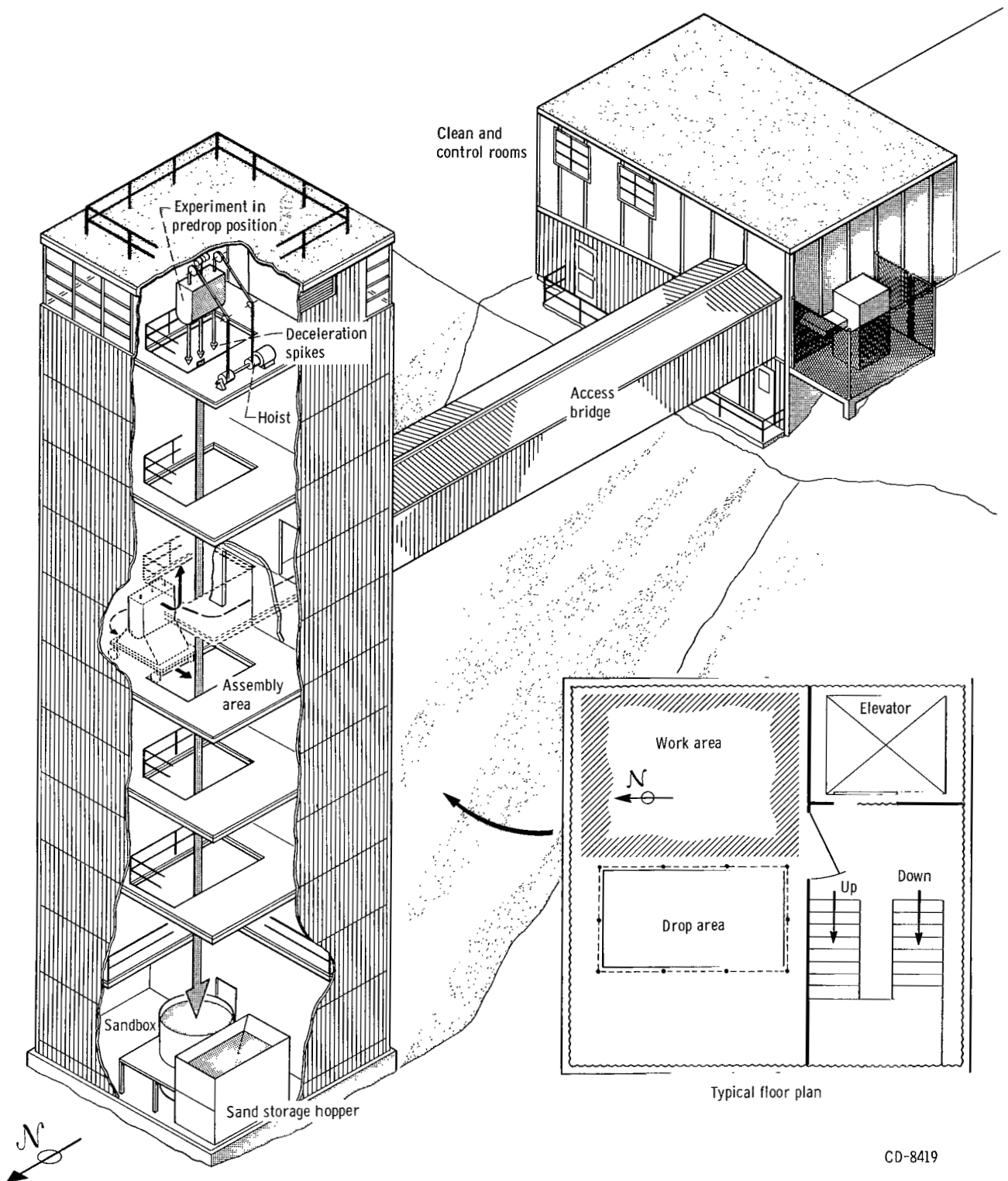


Figure 2. - Lewis 2.3-second drop facility.

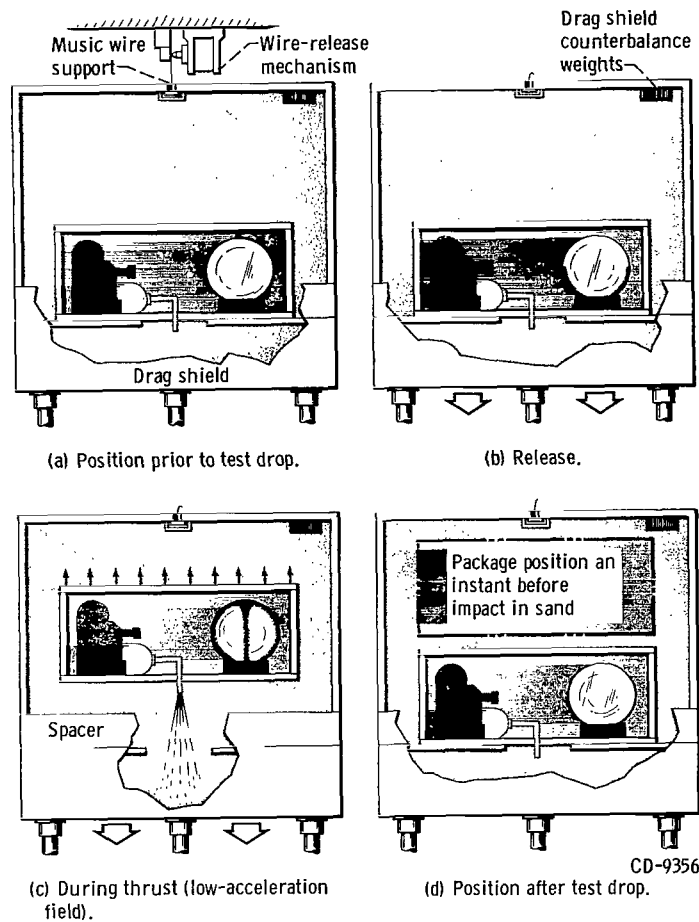
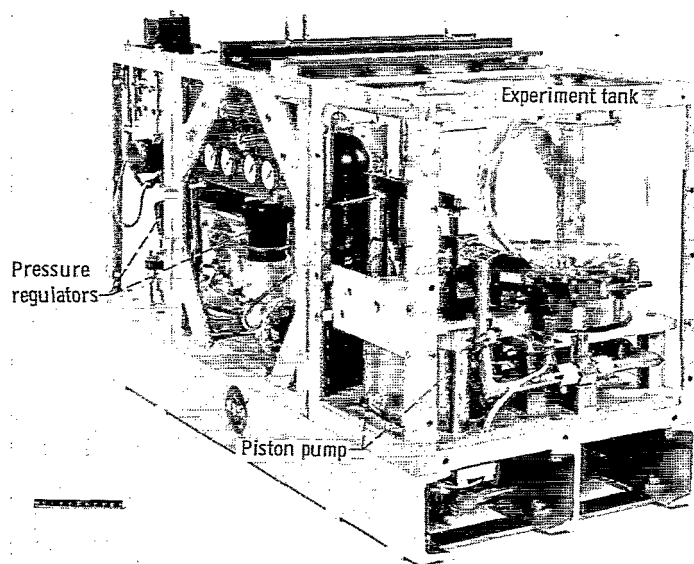


Figure 3. - Sequential position of experiment package and drag shield before, during, and after test drop for thrustor operation.

shield. For the low-gravity tests, the experimental package was initially positioned on the bottom of the drag shield. The thrustor, which was activated within 0.05 second after release of the system, imparted an upwards, precalibrated acceleration to the package, causing a displacement relative to the drag shield. Spacers of different heights were used to allow for different displacements caused by the various acceleration levels. The relative positions of the package and drag shield during a low-gravity test drop is illustrated in figure 3.

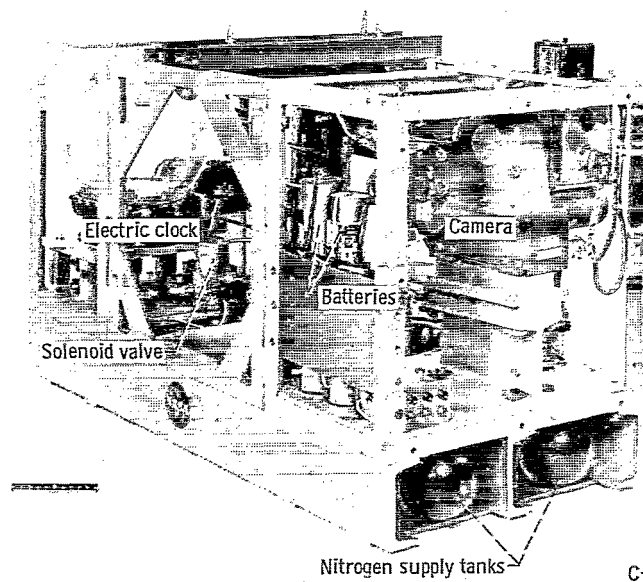
## Experimental Systems

The experimental systems consisted of two separate units, a drop rig for reduced gravity tests and a stationary ground system used for 1-g tests.



C-66-3435

(a) Experiment tank mounted in drop package.



C-66-3434

(b) View showing components.

Figure 4. - Drop package.



Drop package. - The drop package is shown in figure 4. It was a completely self-contained unit which included its own electric, pneumatic pumping, thruster and control systems. Data were collected with a high-speed movie camera mounted on the rig. The electric system consisted of a set of batteries that supplied the necessary power to operate photolights, camera, a clock, and solenoid valves through a control system of relays and timers. A double-acting piston pump, driven by two air cylinders, was used to force the test liquid into the inlet nozzle of the tank and at the same time extract the same amount from the outlet by the reduction in pressure created on the opposite side of the piston. An accumulator tank filled with air supplied the driving force to the cylinders through a pressure regulator and solenoid valve. The pressure regulator setting was used to control the speed of the pump and thereby control the jet inlet velocity. From the pump, the test liquid passed through a turbine flowmeter (used for ground calibration) and then into the sphere.

The cold gas thruster system used to impart the required acceleration to the drop package consisted of three nitrogen accumulators, a quick-response pressure regulator, a solenoid valve, and an outlet nozzle. The thrust level was controlled by the regulator setting and its value determined by a ground calibration technique described under the operating procedures.

One-g test rig. - Figure 5 illustrates the system used for conducting the 1-g tests. A turbine flowmeter whose output could be continuously monitored was used to measure

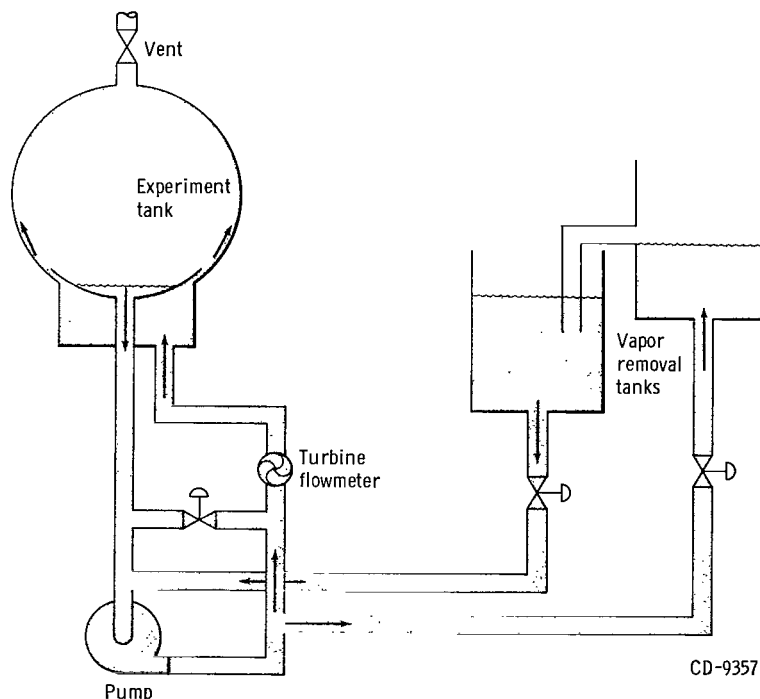


Figure 5. - Schematic diagram of normal gravity test system.

the volume rate of flow to the test tank. The system was designed to accept any one of the three test tanks. A constant speed centrifugal pump with a bypass valve for flow control was used. The system also included two containers located such that some of the entrapped vapor would be vented through them without being recirculated back into the test tank.

## Experiment Tanks

The experiment tanks consisted of three photographically clear plastic spheres of 10-, 20-, and 30-centimeter diameters (figs. 6 and 7). The base of each sphere contained a plenum chamber to provide a uniform inlet velocity. An annular inlet nozzle with an adjustable flow passage into the sphere was located above this chamber. The height of this flow passage was set by the use of shims located at the base of the inlet nozzle for the 20- and 30-centimeter tank and by a screw arrangement on the 10-centimeter tank. Once the base of the tank and the inlet nozzle were assembled, the height of the flow passage could be measured; this dimension was used as the initial wall jet thickness. The outflow passages from the tanks were located through the center of the annular inlet nozzles. The 10- and 20-centimeter tanks were designed to be used interchangeably between the drop package and a 1-g stationary test rig. The 30-centimeter tank was used only for ground tests for two reasons: (1) the physical size of the tank and the associated plumbing and valving were beyond the limiting dimensions of the drop system, and (2) the distance that the liquid jet would have had to travel was too great to complete a test in 2.3 seconds with the velocities under consideration.

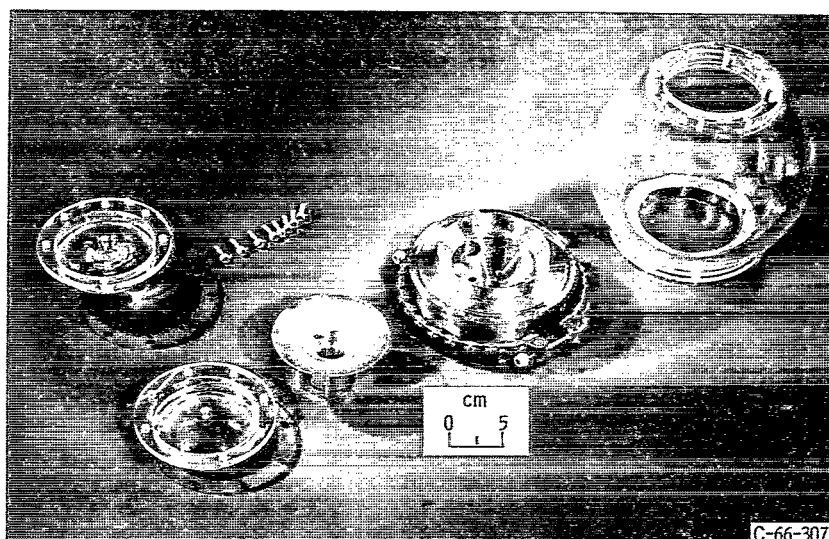
## Test Liquids

Ethanol was chosen as the main test liquid because its specific surface tension most closely resembles that of liquid hydrogen. Mainly because of the ease of handling and pumping and because it was less volatile, water was used as a comparison. The properties of the two test fluids are listed in table I. For photographic purposes a small quantity of dye which had no noticeable effect on liquid properties was added to the test fluids.



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(a) 10-Centimeter-diameter experiment tank.



C-66-3075

(b) 20-Centimeter-diameter experiment tank (disassembled).

Figure 6. - Experiment tanks.

D	d	x	$\delta$ (adjustable range)
10.2	6.6	1.27	0.025 to 0.381
20.0	11.4	2.0	.025 to .254
30.0	17.8	5.0	.025 to .102

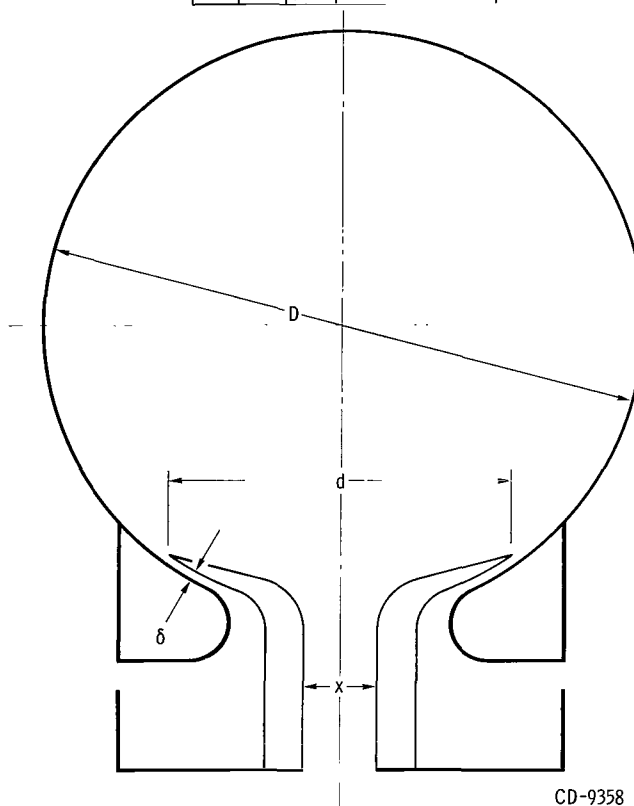


Figure 7. - Experiment tank details. (All dimensions in centimeters.)

TABLE I. - TEST LIQUID PROPERTIES

[Temperature, 20° C.]

Liquid	Density, g/cm <sup>3</sup>	Surface tension, dynes/cm (or $\times 10^{-3}$ N/m)	Viscosity, cP (or $\times 10^{-3}$ N-sec/m <sup>2</sup> )
Ethanol	0.789	22.3	1.2
Water	.998	72.7	1.0

## Operating Procedure

The experiment tanks were prepared by ultrasonically cleaning them to ensure proper surface characteristics before running the tests. The inlet gap thickness was set and measured with feeler gages. The tanks were then assembled and ready for testing.

Normal gravity tests. - In the normal gravity system, the jet inlet velocity was manually adjusted until a critical velocity was obtained. This critical velocity was defined as that which was required to force the jet to reach the top of the tank. The liquid then returned to the tank outlet because of the effect of gravity acting on this fluid stream. This point was photographically recorded on high-speed film. The actual flow rate to the tank was measured with a turbine flowmeter having a quoted accuracy of  $\pm 0.02$  percent in the flow ranges considered. A frequency counter was used as a readout device.

Zero- and low-gravity tests. - In the zero- and low-gravity environments, flow rate adjustments could not be made during the short experimental time available. In these cases, another method for determining velocity requirements was used. Two velocities for each tank configuration were estimated. One of these velocities was selected to be too high and the other, too low to maintain the flow pattern in the low-gravity environment. Each of these velocities was then programmed for a drop test. In this way it was possible to bracket the minimum velocity requirement. Each bracket was then narrowed down by successive experimental drops. The expected flow rate to the experiment tank was set before the drop by adjusting the air pressure used to drive the piston pump. The turbine flowmeter output was recorded as the pumping system was activated. In this manner an approximate flow rate was determined. Since there was no recording system aboard the drop package, it was not possible to obtain flowmeter output during a drop. The actual flow rate during the drop was calculated by photographing a pointer which indicated pump piston displacement and a digital clock with divisions of 0.01 second. Using this data, a curve such as the one in figure 8 was drawn. From this figure, an average pump velocity was calculated. By the use of the continuity equation, an average jet inlet velocity could then be determined. The ground flowmeter readings, which were in very good agreement with the calculated flow rates during the drop, were used only to preset the approximate flow rates.

The low-gravity tests were somewhat more complex than the zero-gravity free-fall drops since they required calibration of thrust level as well as flow rate before each drop. This thrust level was set by placing the test rig on a nearly frictionless air bearing as shown in figure 9, activating the thrust system through a photoresistive switch, and measuring the voltage output from a load cell. The load cell output was photographically recorded from an oscilloscope. The thrust level could be adjusted by a pressure regulator between the tanks and thrust nozzle. The repeatability of the thruster output was  $\pm 4$  percent.

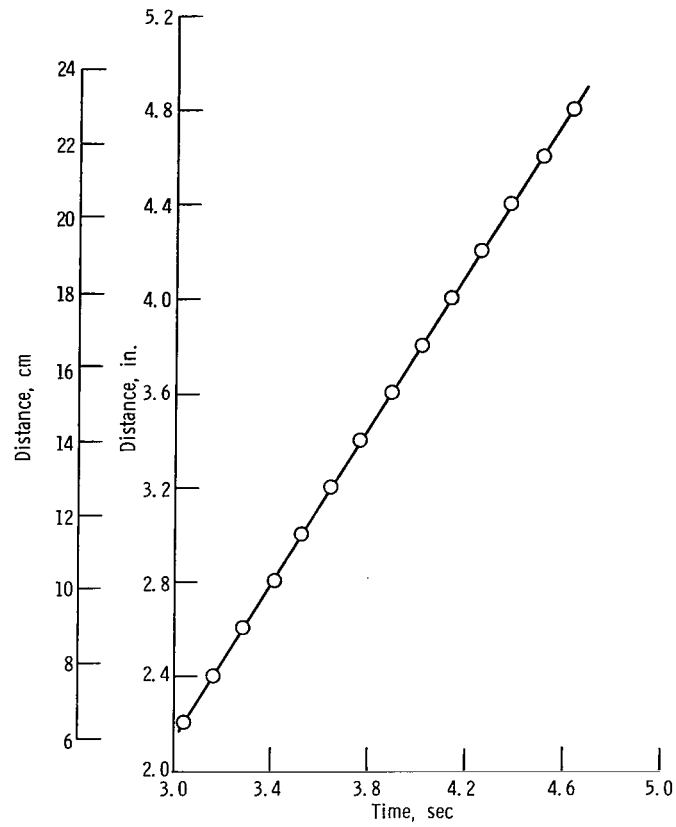


Figure 8. - Typical velocity curve of piston pump during zero-gravity test.

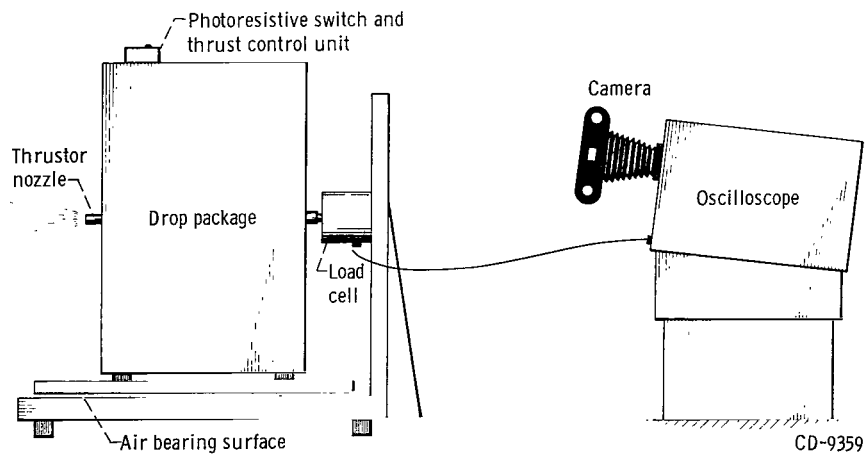


Figure 9. - Thrust calibration system.

Once the ground calibrations of flow and thrust level were completed, the entire drop package was accurately balanced on a strain gage balance rig to ensure that the thrust was directed through its center of gravity; the package was then placed in the drag shield, hoisted to the predrop position, and suspended on a music wire. The system was released by cutting this wire (see fig. 3).

## PRELIMINARY DISCUSSION

The flow pattern examined in this experimental study consisted of an axisymmetric wall jet. This wall jet (as shown in fig. 1) created a circulation pattern in which the fluid was washed along the tank wall and returned to the generating device as a liquid core in the center of the tank.

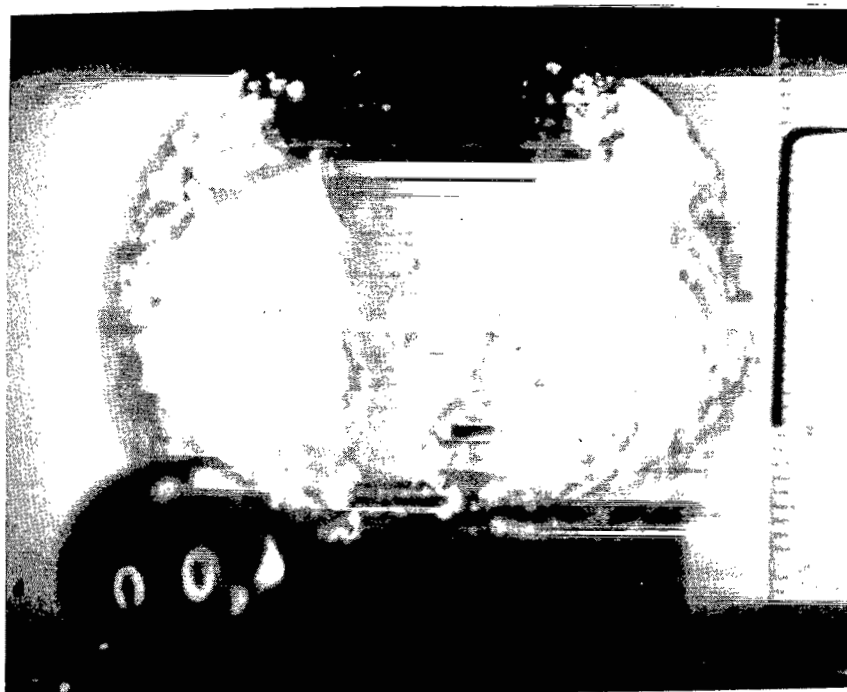
The experiment was conducted to determine the minimum jet inlet velocity required to maintain this flow pattern as a function of the acceleration, geometry, and test fluid of the system. All data were obtained for the steady-state condition where the only liquid in a tank was the amount contained in the thin layer along the tank wall and in the center core. In a reduced gravity environment at velocities lower than critical, the center core was not formed and the liquid collected at one end of the test tank. For velocities less than critical at normal gravity, obviously, the circulating liquid did not reach the top of the tank.

It should be noted that the initial conditions experienced in this system are not identical to those that would be found in a full-size vehicle where the jet is initiated at some finite tank filling level. However, once the pattern is established and maintained, the performance of the systems should be identical to each other if the percent of filling during the flow circulation in the two tanks is the same.

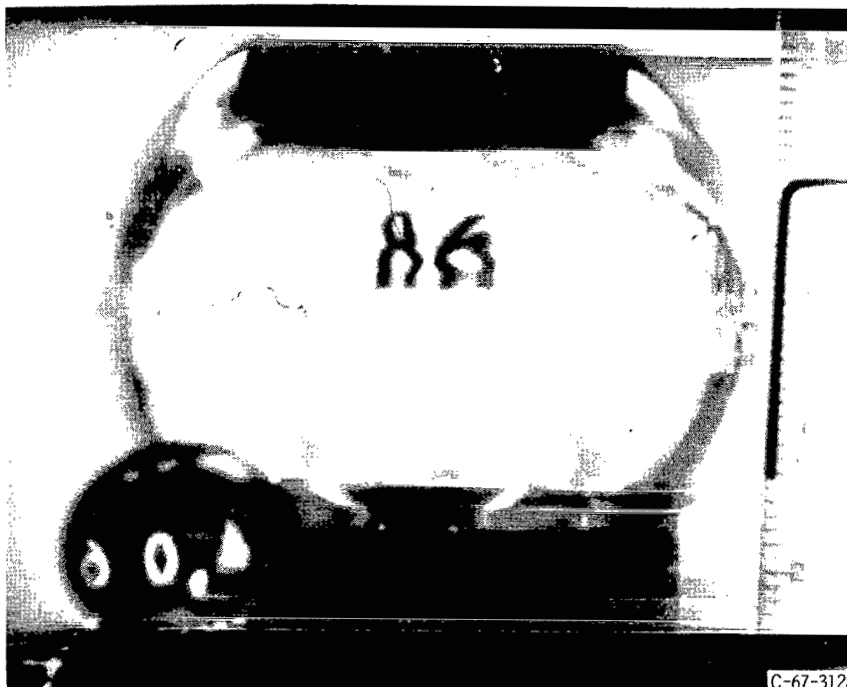
## RESULTS

### Reduced Gravity Photographic Data

Figures 10 and 11 are photographs illustrating the various flow patterns. Figure 10 shows complete and incomplete patterns observed in a 10-centimeter-diameter sphere in a zero-gravity environment ( $<10^{-5} g$ ). Complete and incomplete flow patterns are shown in figure 11 at  $0.93 \times 10^{-2}$  and  $0.47 \times 10^{-2} g$ , respectively. In the pictures of the complete pattern, the center liquid core extends across the entire diameter of the sphere. In the case of the incomplete patterns, the velocity of the leading edge of the jet had considerably dissipated by the time the flow reached the opposite end of the sphere and the veloc-



(a) Complete pattern. Jet inlet velocity, 44 centimeters per second.



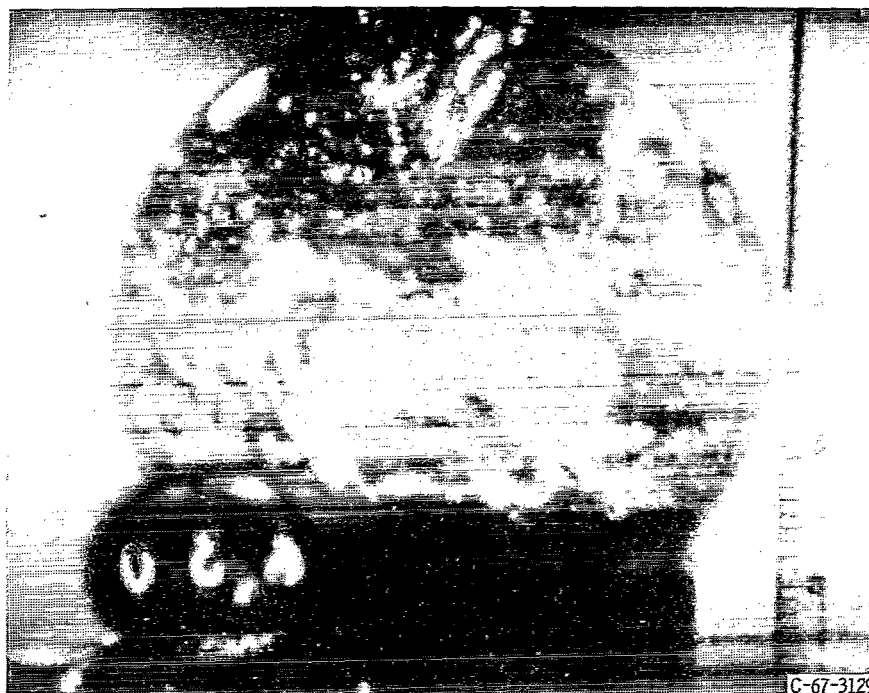
(b) Incomplete pattern. Jet inlet velocity, 25 centimeters per second.

Figure 10. - Flow patterns in 10-centimeter-diameter tank in zero gravity ( $<10^{-5}$  g).





(a) Complete pattern at  $0.93 \times 10^{-2} g$ . Jet inlet velocity, 37 centimeters per second.



(b) Incomplete pattern at  $0.47 \times 10^{-2} g$ . Jet inlet velocity, 15 centimeters per second.

Figure 11. - Flow patterns in a 10-centimeter-diameter tank at reduced gravity.

ity there was not sufficient to overcome the surface tension. As can be seen in the photographs, this surface tension tended to hold the liquid in a collected position and not allow the formation of a central liquid core.

## Effect of Tank Geometry on Velocity Requirements

Ethanol data. - Figure 12 illustrates the dependence of the minimum jet inlet velocity requirement for complete circulation on initial jet thickness. This figure presents

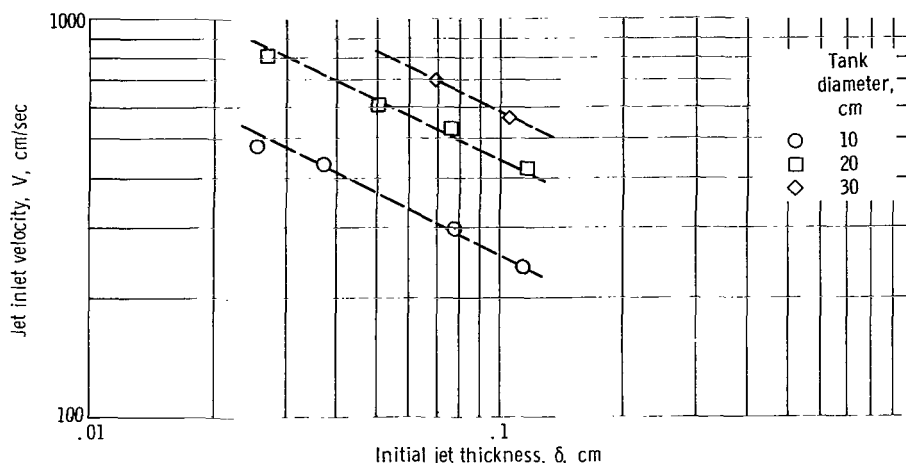


Figure 12. - Velocity required to maintain flow circulation as function of initial jet thickness in normal gravity environment with ethanol.

data for the normal gravity tests with ethanol as the test liquid in each of the three tanks. For each tank the velocity requirement followed the relationship  $V = C(1/\delta)^{1/2}$  where  $C$  is an empirical constant. The exact explanation for this dependence on initial jet thickness is not immediately evident and it is felt that a complete velocity profile and a survey of maximum jet velocity decay would be required to adequately explain this behavior. It should be noted that the initial jet thicknesses used in obtaining this data presented a problem of a thin film flow. The application of this relationship may not be valid for jet thicknesses much greater than the ones tested. A detailed analysis of the jet velocity profile would be required to establish numerical limits for the range of jet thicknesses to which these data may be applied.

A parameter that is commonly used to correlate jet velocities is a nondimensional wall jet ratio of  $L/\delta$  where  $L$  is a characteristic length of the particular system and  $\delta$  is the jet thickness. A similar correlation using  $R/\delta$  was attempted in this work. Figure 13 is a plot of jet inlet velocity as a function of this nondimensional wall jet ratio  $R/\delta$ . This figure shows that these parameters may be used to correlate the data. One straight line,  $V = 41 (R/\delta)^{1/2}$ , whose slope and location were determined by the method of extended differences, was drawn to best fit the experimental data even though the 10-

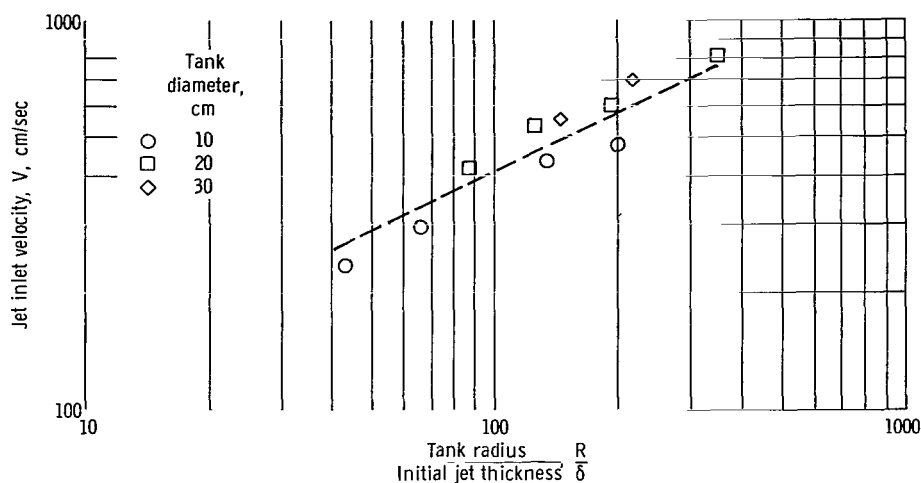


Figure 13. - Velocity required to maintain flow circulation as function of wall jet ratio  $R/\delta$  in normal gravity environment with ethanol.

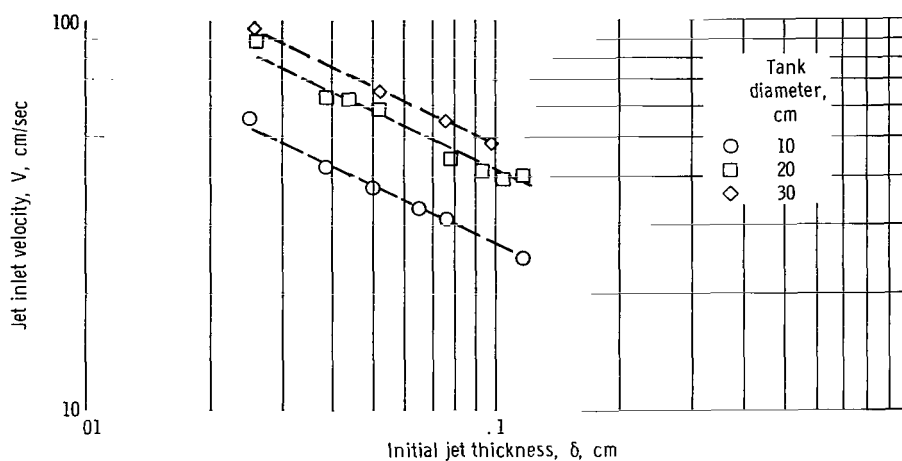


Figure 14. - Velocity required to maintain flow circulation as function of initial jet thickness in normal gravity environment with water.

centimeter data appear lower than the other points. The trend shown by the 10-centimeter points may have been caused by some unavoidable vapor pocket formations in the pumping system. This vapor would have affected both the pump output and the flow-meter signals, and would have resulted in the lower velocity values.

Water data. - The normal gravity tests performed with ethanol were also repeated with water as the test fluid. As noted earlier, water was used as a comparison since it was less volatile and easier to handle. The physical properties of the two liquids (see table I) were not sufficiently different to draw any definite conclusions about the effect of these properties on the flow pattern formation. The water tests served mainly to verify the trends already observed with the ethanol. Figure 14 does indeed show the same trends as figure 12. If these data are again replotted in the same nondimensional form as the ethanol points were, a line,  $V = 37 (R/\delta)^{1/2}$ , results indicating the minimum velocity

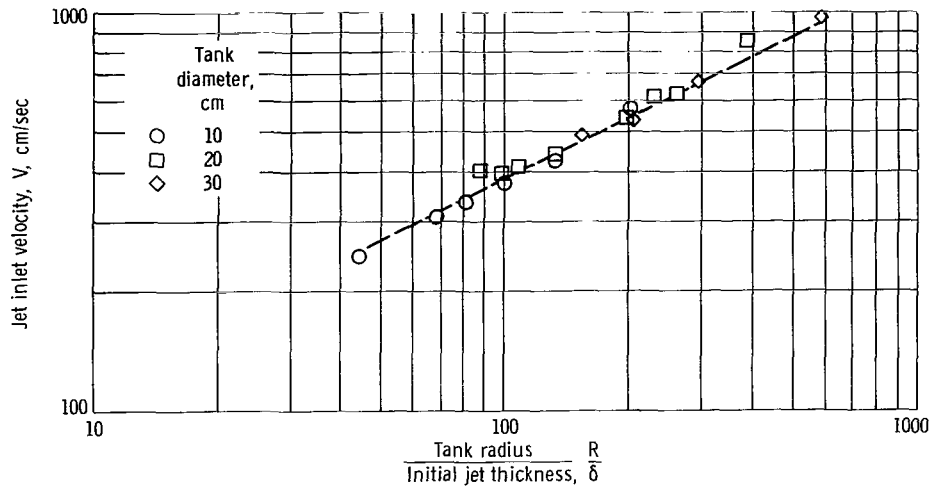


Figure 15. - Velocity required to maintain flow circulation as function of wall jet ratio  $R/\delta$  in normal gravity environment with water.

requirements for water to establish the circulation pattern (see fig. 15). Because of the limitations of the test equipment, it was not possible to test each  $R/\delta$  ratio in each tank. At  $R/\delta = 100, 130$ , and  $200$  where it was possible to do this, identical velocity requirements were observed for each tank. This fact verifies the validity of this scaling relationship.

For the water points very little data scatter exists, which tends to confirm the hypothesis made earlier that vapor pockets were in the probable cause of the spread in the ethanol data.

## Effect of Gravity on Velocity Requirements

### Velocity requirements at low and zero gravity as a function of tank geometry. -

Figure 16 presents the inlet velocity as a function of the dimensionless wall jet ratio at the various acceleration or gravity levels tested, namely,  $0.02, 0.01, 0.005$ , and  $10^{-5}$  times the nominal earth gravity. The latter free-fall condition has been referred to as zero gravity or weightlessness in this report. In figure 16, the solid symbols represent the highest velocity at which an incomplete flow pattern was observed. The open symbols represent the lowest jet inlet velocity at which a complete flow pattern was observed for a given gravity level. It can, therefore, be concluded that the critical velocity required for the flow pattern lies in the bracket between the open and solid symbols. A curve was fitted to each set of brackets indicating the approximate critical velocity required at each specific gravity level.

Examination of these data reveals that the desired flow pattern can indeed be established in a low-gravity environment and that the basic form of the equations of these

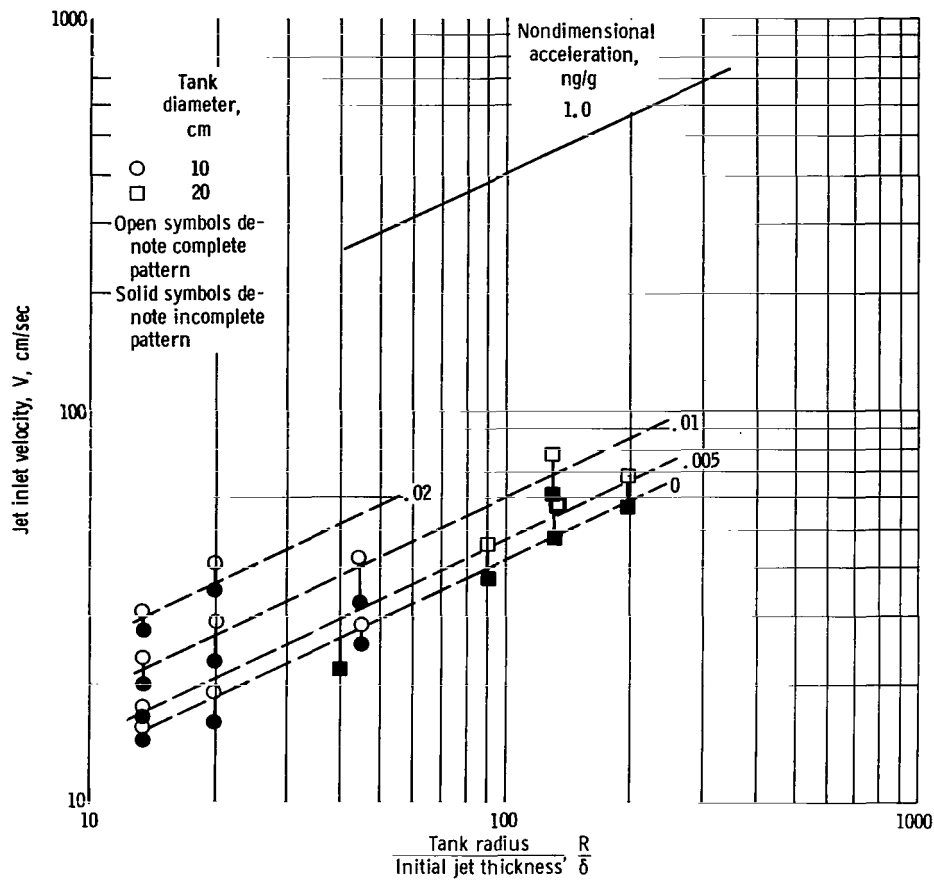


Figure 16. - Velocity required to maintain flow circulation as function of wall jet ratio  $R/\delta$  in low-gravity environments with ethanol.

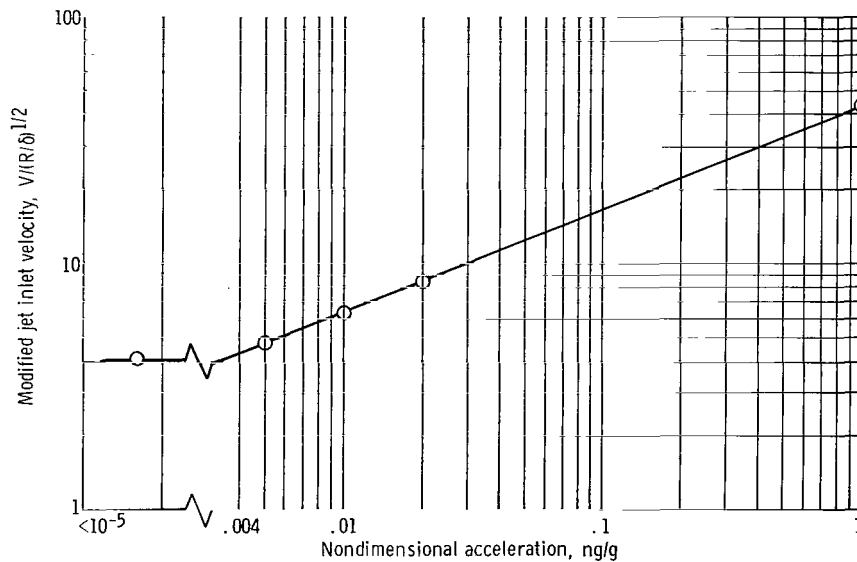


Figure 17. - Effect of gravity on flow circulation requirements for 10-, 20-, and 30-centimeter-diameter tanks. Test fluid, ethanol.

TABLE II. - VELOCITY REQUIREMENTS FOR FLOW PATTERN FORMATION

Test fluid	Non-dimensional acceleration, ng/g	Initial jet thickness, $\delta$ , cm	Jet inlet velocity, V, cm/sec	Flow pattern	Test fluid	Non-dimensional acceleration, ng/g	Initial jet thickness, $\delta$ , cm	Jet inlet velocity, V, cm/sec	Flow pattern				
10-Centimeter-diameter tank					20-Centimeter-diameter tank								
Water	1.0 ↓	0.025	559	(a) ↓	Water	1.0 ↓	0.025	877	(a) ↓				
		.038	412				.038	634					
		.050	372				.043	613					
		.064	333				.051	574					
		.076	304				.076	432					
		.114	238				.092	406					
Ethanol	<10 <sup>-5</sup> ↓	0.114	28.0	Complete	Ethanol	<10 <sup>-5</sup> ↓	0.051	66.6	Complete				
		.114	25.2	Incomplete			.051	56.6	Incomplete				
		.254	19.2	Complete			.076	55.5	Complete				
		.254	16.4	Incomplete			.076	47.1	Incomplete				
		.381	15.3	Complete			.114	46.1	Complete				
		.381	14.5	Incomplete			.114	37.7	Incomplete				
		0.005	17.2	Complete			.254	22.1	Incomplete				
		.005	15.4	Incomplete			.076	57.4	Complete				
		.010	41.3	Complete			.076	76.0	Complete				
		.114	32.0	Incomplete			.076	59.0	Incomplete				
		.254	29.8	Complete			1.0	800	(a)				
		.254	22.8	Incomplete			.051	595	(a) ↓				
		.381	24.0	Complete			.076	533					
		.381	19.9	Incomplete			.114	420					
		.114	29.9	Complete									
		.114	27.5	Incomplete									
		.254	40.8	Complete									
		.254	35.3	Incomplete									
		1.0	.025	478			(a)	30-Centimeter-diameter tank					
		Water	1.0 ↓	.037			432	(a) ↓	Water	1.0 ↓	0.025	952	(a) ↓
				.076			299				.051	668	
				.114			235				.074	549	
				.096	490								
Ethanol	1.0 ↓			(a) ↓	Ethanol	1.0 ↓	0.068	694	(a) ↓				
							.102	554					

<sup>a</sup>Critical velocity.

curves is identical to those presented for the 1-g case. For reference purposes the 1-g line is also included in figure 16. The velocity for the zero-gravity flow pattern formation is on the order of one-tenth of that required for the 1-g test. All the partial gravity points fall in between these limits.

Velocity requirements as functions of gravity level. - The effect of gravity on flow circulation requirements can be more clearly observed by plotting a modified jet inlet velocity, defined as  $V/(R/\delta)^{1/2}$ , against a nondimensional acceleration  $ng/g$ . Figure 17 is such a plot. Each acceleration level in figure 16 is represented by one point in figure 17.

A wide break is shown in the curve at very low acceleration levels. In this range (the part of the curve to the left of the break), the data show an independence of gravity, since in this area surface tension will dominate the flow pattern. The right side of the curve indicates a region where gravity will have a significant effect. The curve on the right side of the break is expected to asymptotically approach that on the left side. If, for the right side of this curve, a Froude relation (the ratio of inertia to gravity force) were the only governing parameter, one would expect a slope of 0.5. However the measured slope is 0.43. From these results, it may be concluded that a Froude relation may not be used alone to entirely correlate the data. The significant result to be obtained from this data is the fact that all the points fall on a straight line, thus confirming the validity of correlating the applied acceleration with the modified jet inlet velocity. For reference purposes, the basic data obtained in conducting all the tests are presented in table II.

## SUMMARY OF RESULTS

An experimental investigation of the effect of gravity on forced circulation patterns in spherical tanks was conducted. The desired flow pattern consisted of a three-dimensional axisymmetric wall jet. The jet was forced along the wall of the tank and returned to the generating device as a liquid core in the center of the tank. The tests were conducted with three geometrically similar tanks of 10-, 20-, and 30-centimeter diameters over a gravity range from 1 to  $< 10^{-5} g$ . The following results were obtained:

1. The desired flow pattern was established and sustained under all conditions.
2. The minimum velocity required to maintain the flow pattern was correlated with respect to the tank radius  $R$  and initial jet thickness  $\delta$  by the parameter  $R/\delta$ .
3. The minimum velocity required to maintain the flow pattern was correlated with the acceleration of the tank system by a modified jet inlet velocity  $V/(R/\delta)^{1/2}$  where  $V$  is the jet inlet velocity.

4. The critical velocity was independent of the applied acceleration (gravity level) and approached a limiting value at very low gravity levels. At the higher accelerations, the critical velocity varied with  $(ng/g)^{0.43}$  where  $n$  is a coefficient and  $g$  is acceleration due to gravity.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, August 11, 1967,  
124-09-03-01-22.

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